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OSIRIS-REX POST-TAG OBSERVATION TRAJECTORY DESIGN AND NAVIGATION PERFORMANCE

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NASA's OSIRIS-REx spacecraft successfully collected a sample of asteroid regolith from the surface of near-Earth asteroid Bennu in October of 2020. Subsequent imaging of the sampler head showed material leaking from the collection mechanism, thus stowage of the sample precluded execution of any planned maneuvers in the following days. Optical navigation imaging also ceased in the days following sample collection. The desire to image the sample site to investigate the results of the spacecraft-to-surface interaction led to the Navigation team designing a trajectory to return to Bennu after several months in order to image the surface one final time. After several iterations a trajectory design was created that satisfied the numerous constraints that were levied in order to place utmost importance on the safety of the spacecraft and stowed sample, while also closely emulating previously obtained imaging conditions to provide a close comparison of site pre- and post-contact. Significant analysis was necessary in order to reliably reacquire the asteroid after several months without optical navigation imagery. The final design required five maneuvers to return the spacecraft to Bennu and perform a final flyby of the asteroid at a distance of 3.8 kilometers. Successful execution of the phase provided key insights regarding the performance of the sample collection activities and the subsurface composition of the asteroid.

INTRODUCTION

NASA's Origins, Spectral Interpretation, Resource Identification, and Security–Regolith Explorer (OSIRIS-REx) asteroid sample return mission[1] arrived at target near-Earth asteroid Bennu in late 2018, and spent over two years in proximity operations near the asteroid. Throughout this period, the asteroid Bennu was observed at unprecedented levels of detail.[2] The Detailed Survey mission phase, executed in Spring 2019, in particular was designed to observe the asteroid at ranges from 3-5 km and under a wide variety of lighting conditions in order to produce a variety of maps of the entire asteroid surface, which were critical for determining potential sample site locations.[3,4] In late 2019 and early 2020, the mission performed Reconnaissance of several candidate sampling sites[5] and eventually settled on two finalists: the prime site Nightingale located at a Bennu latitude of 56 degrees, and the backup site Osprey, located near Bennu's equator. After 2 rehearsals at the Nightingale site, years of effort at Bennu culminated in a successful Touch-and-Go (TAG) maneuver, wherein the spacecraft briefly contacted and collected a sample from the Nightingale site on October 20, 2020.[6]

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The TAG sequence had several different possible exit conditions, dependent on whether the spacecraft touched down on the surface of Bennu or aborted at some point earlier in the sequence. The TAG sequence itself began with the orbit departure maneuver (ODM), at which point the spacecraft left its 'safe-home' frozen terminator orbit.[7] Shortly after completing this maneuver the spacecraft enabled a 40 cm/s back-away burn (BAB) to be executed either in the instance of an anomaly detected on-board, or upon successful contact with the asteroid surface. If an anomaly were autonomously detected at some point after orbit departure during the descent to the surface, the spacecraft would immediately perform the BAB to quickly move away from the asteroid and keep the spacecraft safe. If there were no anomalies, the sequence was designed to perform the BAB approximately 5 seconds after detecting surface contact. In this scenario, the amount of collected sample would be evaluated in the weeks following TAG to determine if sufficient sample was gathered, or if another attempt would be required. Without knowing how TAG would execute in advance, the post-TAG trajectory design had to account for all possible outcomes, which were distilled down to 2 possible situations: 1) TAG is not successful and the spacecraft must return to Bennu for another attempt, and 2) TAG is successful and the spacecraft can drift away until execution of the asteroid departure maneuver in May 2021. However, in the scenario that the spacecraft touched down but did not collect enough sample, this information would not be known until over two weeks after TAG, at which the spacecraft would be 100's of kilometers away from Bennu due to the size of the BAB. This distance would greatly increase the difficulty of returning to the asteroid and would require several months to be prepared to perform a second sampling attempt. Thus the team chose to include the first maneuver in the recovery sequence design, scheduled for 4 days after TAG, regardless of success. The next maneuver in the recovery sequence was scheduled to be executed several weeks later, and could be cancelled if the sample was safely stowed in the Sample Return Capsule (SRC).

In order to keep the team focused on collecting and stowing a sample, there was no formal discussion or plans made on any possible post-TAG activities. However, the science team did have a desire to image the Nightingale site at some point after TAG. Imaging of the surface post-TAG was motivated by the desire to: (1) detail the change in topography that was a direct result of the spacecraft contact with the asteroid surface, (2) provide additional insight on the performance of the TAG maneuver and the location of spacecraft contact on the surface, and (3) give more insight to the surface properties and subsurface structure of the asteroid. Figure 1 is an example of the desired results from such an imagining campaign.

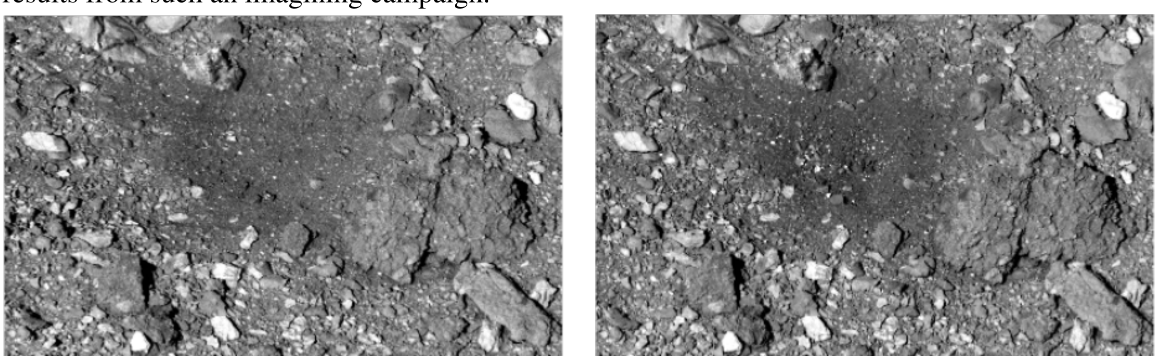


Figure 1: Comparison of Nightingale TAG Site pre-(left) and post-TAG (right)

This paper describes the trajectory design and navigation performance of the OSIRIS-REx mission during the period of time following TAG, until execution of the asteroid departure maneuver in May 2021. First, the baseline plans for both a successful and unsuccessful TAG will be discussed,

followed by the reality the team experienced after execution of TAG in October 2020. Next, the paper will describe the various constraints and requirements imposed on the trajectory design for possible imaging of the Bennu surface post-TAG, followed by the design of the trajectory necessary to achieve these conditions. The paper then discusses the extensive optical navigation (OpNav) analysis and planning required to successfully execute the design. Finally, the execution performance will be presented, with a side-by-side comparison of the Nightingale TAG site before and after-TAG to detail the change in topography that was a direct result of spacecraft contact with the asteroid surface.

NOMINAL POST-TAG TRAJECTORY DESIGNS

Prior to TAG, two different trajectory designs had to be maintained such that a mission plan was in place regardless of the outcome. In practice, the design was primarily focused on returning to orbit in the case of a failed TAG. If TAG was found to be successful, any maneuvers after the first in the plan were to be cancelled and the spacecraft would slowly and safely drift away from Bennu without any further adjustments necessary. A comparison of the two options are shown in Fig. 2, where a driftaway following a successful TAG is in black and a return to orbit is shown in blue. Note that the two trajectories are identical until after the second recovery maneuver, at which point the return to orbit trajectory starts to rapidly reduce the range to Bennu. The return to orbit process required 5 maneuvers and approximately 4 weeks, which enabled a potential second TAG attempt in January 2021. Also included is the 'no-burn' option in red, which performed no maneuvers following TAG, and was analyzed as a possible contingency scenario.

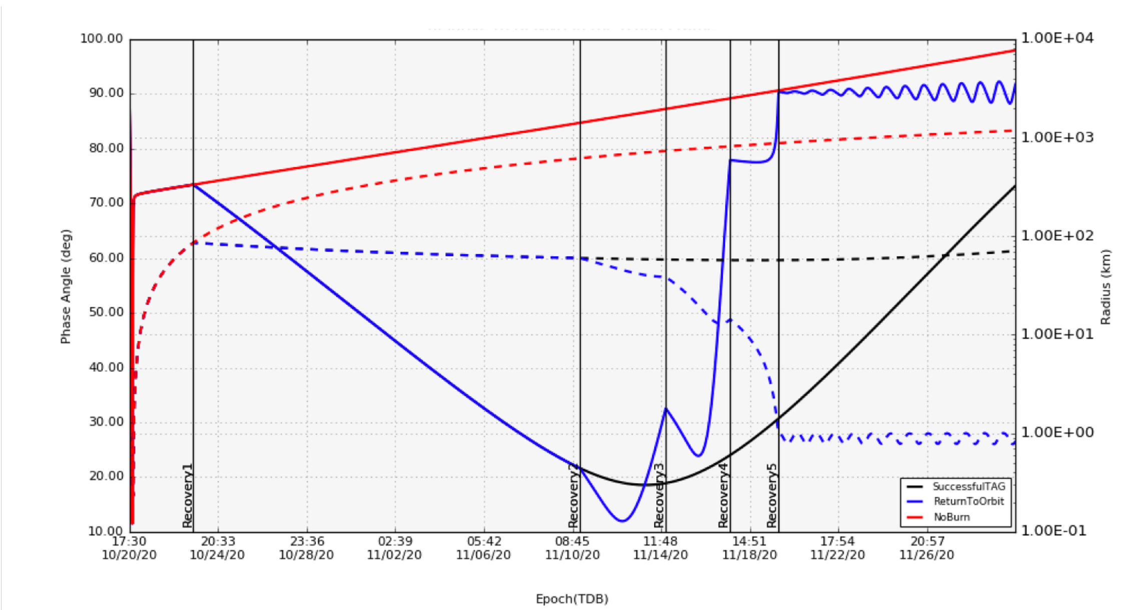


Figure 2: Trajectory profile comparing OSIRIS-REx post-TAG trajectory options. The solid lines are the phase (Sun-Asteroid-Probe) angle and the dashed lines are the range to Bennu, with the log scale on the right.

While evaluating the actual performance of the sample collection attempt in the days after October 20, it became clear via imaging that the Touch-and-Go Sample Acquisition Mechanism (TAGSAM) had collected a significant amount of asteroid material, but some of the material was observed to be

leaking out in to space. At this critical juncture the team made the decision to proceed with stowing the collected sample early and cancel all non-vital spacecraft activities in order to minimize the amount of lost sample. This decision precluded execution of the first post-TAG recovery maneuver, and thus the spacecraft most closely followed the red trajectory in Fig. 2. The spacecraft continued to drift away from the asteroid, reaching a distance of nearly 1000 km one month after TAG, and thus it seemed unlikely that the spacecraft would return to Bennu again.

RETURN TO BENNU TRAJECTORY DESIGN

After successfully stowing the sample on October 29, 2020, the team began to discuss and contemplate possible ways to return to Bennu in order to image the Nightingale site. These images would not only provide information on the performance of TAG itself, but were also desired by the science team to collect data on the regolith properties of the surface and the composition of any newly surfaced material that was possibly exposed during TAG execution. Analysis performed by the Navigation team showed that the Δv-optimal asteroid departure date to begin the return cruise to Earth was in May 2021, providing the team some time to attempt an observation campaign. Thus the Navigation team began looking at possible designs to return to Bennu from a great distance in order to image the surface one final time. This entailed essentially repeating a portion of the original Approach to Bennu from 2018 but with additional constraints to prioritize the safety of the spacecraft and the collected sample.

Trajectory design for a return to Bennu began in earnest in December 2020, with the intention of performing the first maneuvers in mid-January 2021. By this time, the spacecraft was nearly 2200 km from Bennu and required significant time and ample Δv to return. The reconstructed flight profile of OSIRIS-REx during the drift-away period in late 2020 is shown in Figure 3. In addition to the large distance between the spacecraft and Bennu, the spacecraft had also drifted behind the asteroid when viewed from the Sun due to solar radiation pressure (SRP). With the last OpNav image shuttered just after TAG in late October, re-acquisition of the body would be complicated and impose additional constraints on the trajectory design. The concept of operations (ConOps) used for re-acquiring OpNavs throughout this period is covered in greater detail in the next section. The design of the return to Bennu was imposed by numerous constraints and requirements, which can be organized by their source: spacecraft safety, schedule, and science observations.

Spacecraft Safety Constraints

With an asteroid surface sample already successfully collected and stowed, the trajectory design had to prioritize minimizing risk to the spacecraft and the stowed sample. One facet of this was to ensure that any portion of the return trajectory was guaranteed to have no possibility of impact with Bennu if no future maneuvers were performed, whether due to a missed uplink, spacecraft safe mode entry, or any other anomaly. Similarly, because this mission phase provided bonus science and was not necessary to meet the primary mission objectives, if any maneuver during this phase were missed, there would be no attempt to recover. Instead, the imaging campaign would be abandoned and the spacecraft be allowed to drift away from Bennu until execution of the asteroid departure maneuver (ADM). As an extension of the lower risk design for this phase, the team had a desire to minimize the overall number of activities in order to accomplish the desired imaging. Early trajectory designs attempted to accomplish the entire return trajectories with just 2 maneuvers, but these designs did not close when analyzed further. Eventually, a 5-maneuver design was found that did reliably provide the necessary imaging conditions, while guaranteeing spacecraft safety.

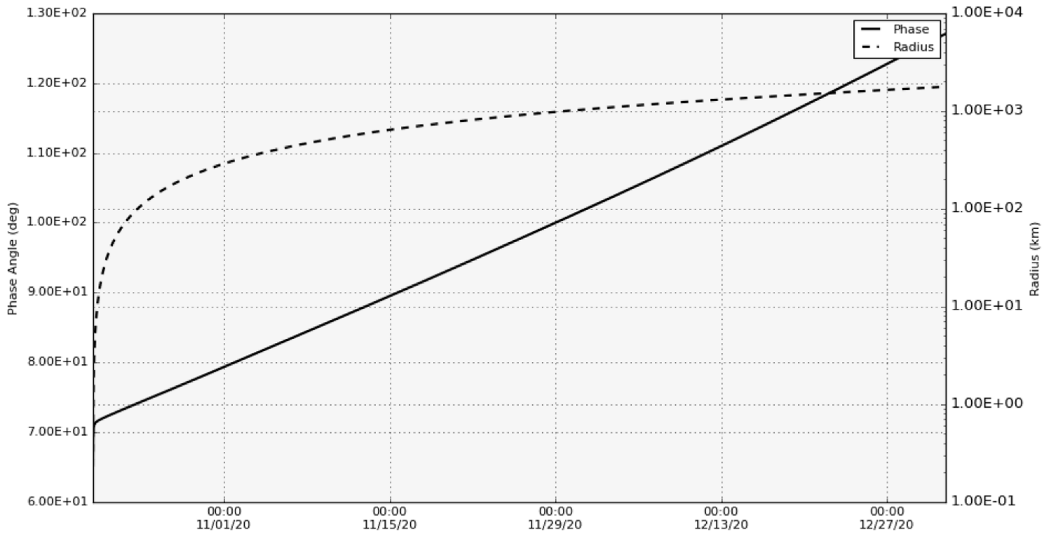


Figure 3: As-flown OSIRIS-Rex trajectory profile of the post-TAG driftaway. The solid line is the phase (Sun-Asteroid-Probe) angle and the dashed line is the range to Bennu, with the log scale on the right.

Any maneuver which required pointing the instrument deck within 45 degrees of the Sun had to be decomposed in to 2 separate segments that were executed individually to provide a resultant Δv in the desired direction. This constraint was applicable throughout the entire mission and not unique to this phase. The 45 degree constraint was also applicable for OpNav imaging: images of Bennu could not be acquired if they required pointing the instrument deck within 45 degrees of the Sun.

The spacecraft trajectory following TAG was primarily influenced by Bennu's gravity and SRP following completion of the BAB. Over the course of several months of propagation, the spacecraft naturally drifted "behind" the asteroid when viewed from the Sun, which coincides with a phase angle of greater than 90 degrees in Figure 3. By the time of the first maneuver to return to Bennu in mid-January, SRP had pushed the spacecraft to a phase angle of 140 degrees, which not only guaranteed that the first maneuver would be decomposed, but also precluded OpNav imaging until a later date when the spacecraft phase angle was guaranteed to have returned to a value below 135 degrees. The desire was to design the trajectory to enable OpNav imaging as early as possible in order to reduce trajectory prediction errors to levels similar to those obtained during proximity operations, which would be necessary in order to reliably image the Nightingale TAG site and provide the necessary imaging geometry.

Table 1: Summary of the OSIRIS-REx spacecraft thruster suites and Δv ranges.

Thruster Suite	Thrust	# of Thrusters	Min. Δv	Max. Δv
Main Engine (ME)	200 N	4	50 m/s	N/A
Trajectory Control Maneuver (TCM)	22 N	6	50 cm/s	50 m/s
Attitude Control System (ACS)	4.5 N	16	1 cm/s	60 cm/s
Low-Thrust Reaction Assembly (LTR)	0.9 N	2	0.08 mm/s	3 cm/s

The OSIRIS-REx spacecraft had 4 sets of thrusters available for maneuver execution, as summarized in Table 1. The ACS thrusters were the primary set utilized while in proximity operations at Bennu, but could not provide a Δv of more than 60 cm/s. The TCM thrusters, the next largest set, were last used in October 2018 during the initial Approach to Bennu.

Schedule Considerations

With the trajectory design beginning in December 2020, the return to Bennu could begin no earlier than mid-January 2021 in order to account for human factors and to reduce workload for the team during the 2020 holiday season. The first weekend in April was also avoided to the best extent possible due to the Easter holiday for the same reason.

The team's ConOps for OpNav planning required 6 weeks of development. To reduce the uncertainty in planning for these observations, this process would wait until the return to Bennu began, thus placing the OpNav reacquisition in the late-February 2021 timeframe, at the earliest. Any maneuvers prior to this point had to be designed using only radio metric data for estimation of the current trajectory. Similarly, the science observation planning process required 8 weeks of development, which set a no-earlier-than date of mid-March for acquisition of the science observations.

With the ADM nominally scheduled for May 10, the team wanted several weeks to focus on the design and implementation of this large, main engine maneuver. Thus, the conclusion of the post-TAG observation campaign had to be at least 3 weeks prior to ADM, effectively providing a no-later-than date of April 19 execution of the science observations.

Finally, analysis suggested that the team could relax the 24-hour "late update" timeline to perform updates of the on-board spacecraft ephemeris or maneuver designs. These late updates were common during proximity operations at Bennu, but removing them greatly helped reduce the risk of a missed uplink and eased workload on the team. In keeping the duration between the final maneuver design and execution to no less than 72 hours, every uplink had a backup opportunity, and no second- or third-shift work was required.

Observation Design and Constraints

The observations of the Nightingale TAG site were designed with the objective to closely mirror the observation conditions achieved during the second survey station of the Detailed Survey mission phase.[3] By repeating the illumination conditions, the new imaging would provide a close comparison of the Nightingale site before and after TAG. Exact duplication of the conditions was not possible due to Bennu being at a different location in its orbit than during the pre-TAG imaging performed in 2019. The desired observation geometry as flown during the Detailed Survey phase is shown in Figure 4, and a summary of the delivery requirements for the trajectory design is included in Table 2. In particular, the spacecraft was to fly a South-to-North hyperbolic trajectory at a local solar time of 12:30 pm - slightly to the afternoon side of Bennu from the asteroid-Sun line when following the asteroid's rotation. Observations would be centered at Bennu's equator, but were targeted to image the area surrounding the Nightingale TAG site located at a Bennu latitude of 56.04 degrees.[6] Finally, the observations were targeted to occur at a Bennu radius of 3.8 km with a spacecraft velocity of approximately 5 cm/sec at closest approach. While the delivery requirements as listed in Table 2 are relatively stringent, ultimately these were not strict constraints and did not take precedence over spacecraft safety and easing the team's workload. In addition, the flight software used on-board the spacecraft to determine the direction of nadir could not be used if the spacecraft

phase angle fell below 0.86 deg, making the effective constraint on Solar Longitude ± 6.6 degrees (3σ).

One final difference between the pre- and post-TAG imaging is that the post-TAG imaging would not utilize any 'timeshift' in the design and execution. Details on how this was utilized are contained in Wibben et al.[4] The timeshifts were essentially an adjustment in the science observation sequence start time in order to center the observations around when the spacecraft was predicted to pass Bennu's equator. This information was communicated by the Navigation team using the latest knowledge of the spacecraft trajectory in the 24 hours prior to execution. To compensate for not using this capability, the science observation window was extended to nearly 10 hours for the post-TAG imaging to help guarantee coverage of the asteroid and particularly the Nightingale TAG site, as opposed to 5 hours used during Detailed Survey, .

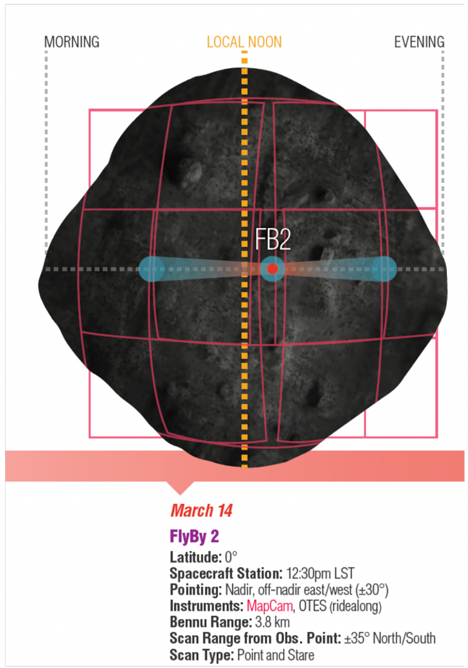


Figure 4: Desired observation geometry for the post-TAG imaging, mirroring the second Detailed Survey flyby conducted March 14, 2019.

Table 2: Post-TAG observation geometry target and constraints

Parameter	Nominal Value	Delivery Requirement (2σ)
Local Solar Time	12:30 PM	24 min
Radius (km)	3.8	0.3
Bennu Latitude (deg)	0.0	5.0
Solar Longitude (deg)	7.5	6.0

Overview of Final Trajectory Design

The final design that satisfied all of the above constraints and requirements provided an opportunity for science observations of the Nightingale site on April 7, 2021. The Post-TAG Observa-

tions (PTO) trajectory design required execution of 5 maneuvers, with the first to be executed on January 14, 2021. A summary of the nominal maneuver designs to complete these post-TAG observations are included in Table 3. Due to the large distance between the spacecraft and Bennu at the time of execution, the first maneuver (PTO1), required use of the TCM thruster suite in order to achieve the necessary Δv. Further, due to the high phase angle, PTO1 had to be decomposed into two separate, smaller maneuvers. Each of these had a design Δv of approximately 73 cm/s, which placed the design slightly out of reach of the ACS thruster suite and at the low end of the TCM thrusters. Expected maneuver execution errors for the TCM thrusters are much larger in this performance regime than a similar sized maneuver on the ACS thruster suite. In order to guarantee the post-PTO1 trajectory was safe the target had to be biased significantly away from Bennu. For comparison, a Monte Carlo analysis of PTO1 when executed on the TCM thrusters demonstrated a Bennu arrival B-Plane error ellipse semi-major axis of approximately 190 km, as opposed to just 50 km if the maneuver were able to be executed on the smaller ACS thrusters. The B-Plane error ellipses for each of the first four maneuvers in the trajectory are shown in Fig. 5, with Bennu located at the origin, outside of each 3σ ellipse. No ellipse is included for the final maneuver, PTO5, as most of the trajectories were not hyperbolic at the time of closest approach. These figures do not use the traditional B-Plane definition due to the low relative velocities and Bennu's low gravity, but instead use an equivalent formulation using the spacecraft velocity and angular momentum vectors. Note that each activity listed in Table 3 has a final Data Cutoff (DCO) of at least 72 hours, except for the final ephemeris update just prior to the science observations. Due to the final maneuver, PTO5, being executed approximately 72 hours prior to the science observations, the DCO was moved to the day after PTO5 in order to reconstruct the maneuver execution and provide an accurate prediction of the spacecraft trajectory during the flyby.

Table 3: Activities for PTO Mission Phase Reference Trajectory

Activity	Date	Thruster Suite	Δv (cm/s)	Data Cutoff (days)	Bennu Range (km)
PTO1	14-Jan-2021	TCM	146.6 (2×73.3)	E-10	2197.8
PTO2	06-Mar-2021	ACS	30.9	E-3	265.1
PTO3	20-Mar-2021	ACS	39.5	E-4	93.5
PTO4	27-Mar-2021	ACS	26.0	E-3	40.0
PTO5	04-Apr-2021	ACS	10.6	E-3	6.5
PTO Observations	07-Apr-2021			E-2	3.8

A profile of the trajectory showing the range to Bennu and the phase angle along with the 1, 2, and 3σ Monte Carlo errors is shown in Figure 6. Notably the long propagation period between PTO1 and PTO2, along with the relatively large execution errors due to the small TCM maneuvers for PTO1 result in large trajectory dispersions throughout this time period until the later maneuvers are performed on a more frequent schedule. Also marked on this figure is the maximum allowable phase angle for acquiring OpNavs at 135 degrees in order to keep the instruments pointed away from the Sun. For planning purposes, the resumption of OpNav observations had to be selected such that the trajectory was guaranteed to be below this limit. Thus, the first OpNavs were planned to be shuttered on February 23rd, which corresponds to the timing of when the 3σ phase angle fell below this limit. Finally, while not shown in the plot, scheduling the observation flyby for early

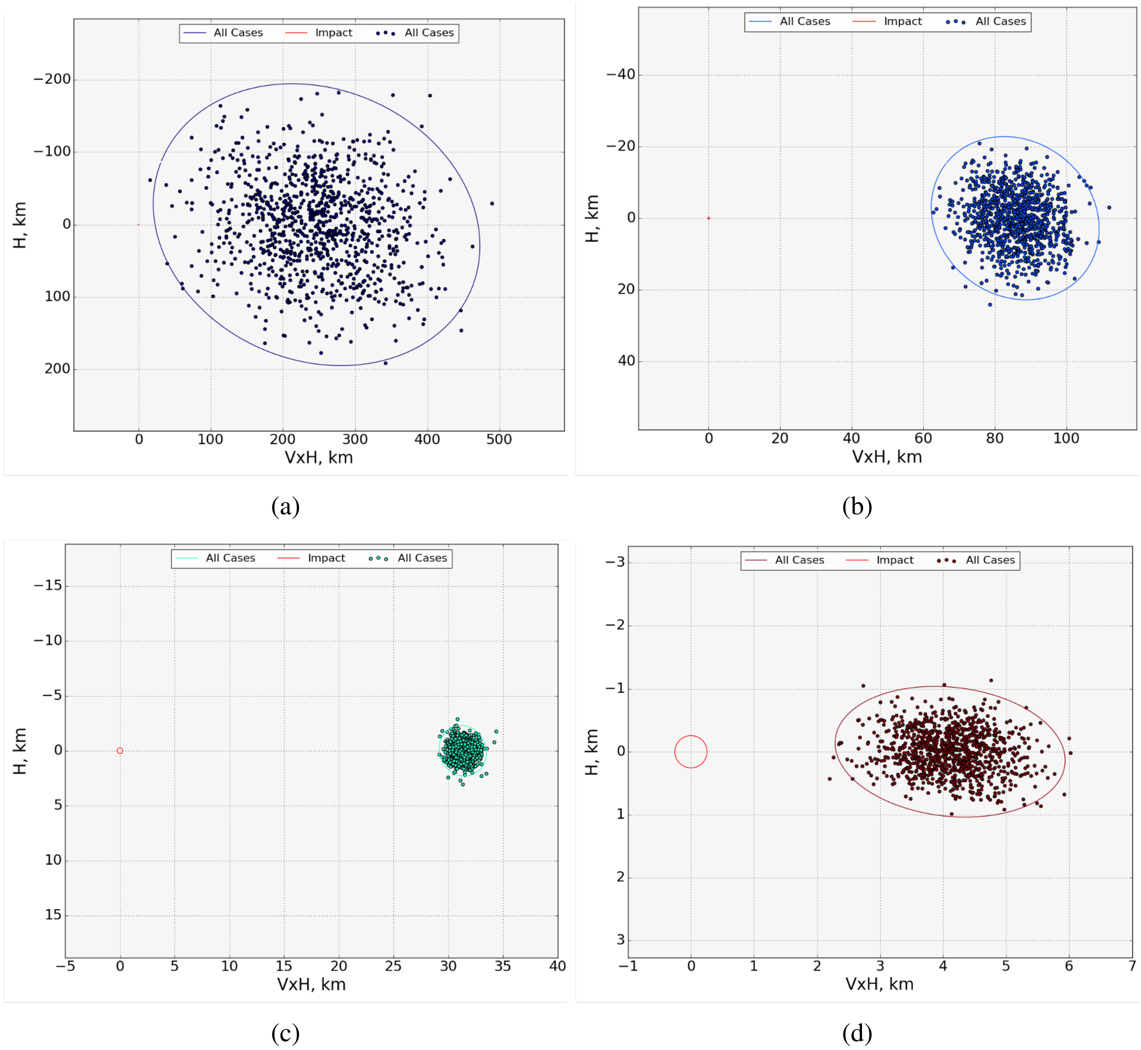


Figure 5: Monte Carlo analysis closest approach error ellipses for (a) PTO1, (b) PTO2, (c) PTO3, and (d) PTO4. Bennu impact ellipse is located at the origin in each plot.

April placed the spacecraft over 350 km from Bennu at the time of the ADM approximately one month later, which satisfied any potential safety concerns with the execution of that maneuver and provided ample time for the team to focus on its design.

As mentioned previously, the final leg of the trajectory was designed to closely mirror an observation flyby performed during the Detailed Survey mission phase. A zoom in of the trajectory profile for the science observation portion of the PTO trajectory is shown in Figure 7. The 2σ error bounds as expressed in Table 2 are included, showing that the range and solar longitude constraints are satisfied to 2σ for the entire observation window. The solar latitude is along the direction of motion of the spacecraft during the observation leg and the constraint is only applicable at the target observation center time, at which point all trajectories fall within the ± 5 degree constraint.

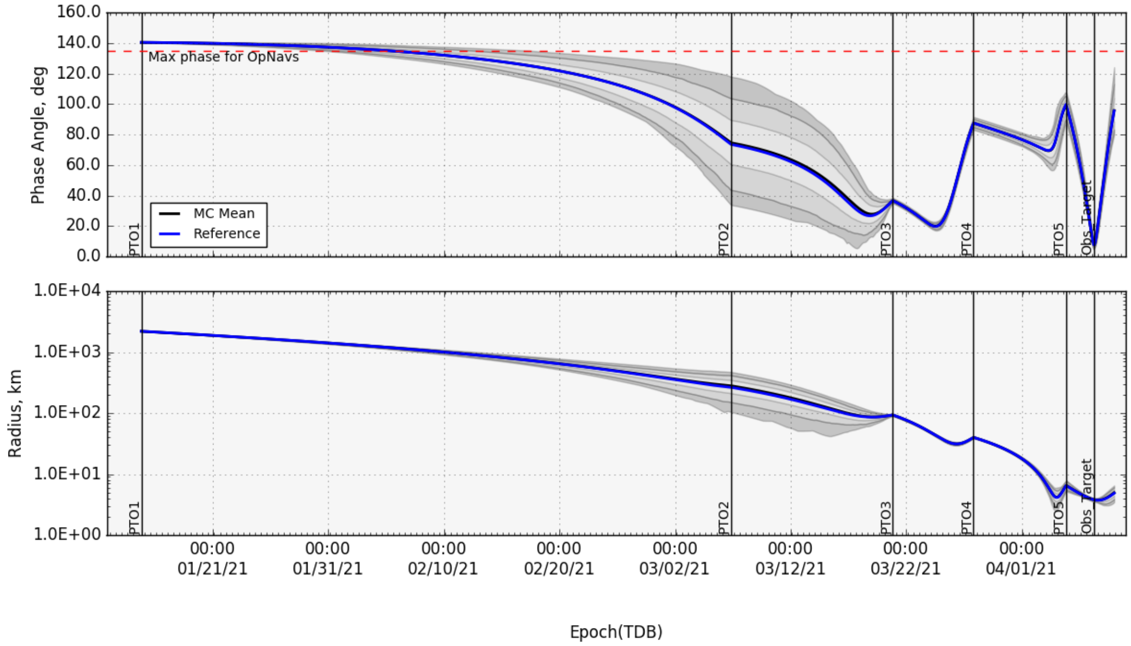
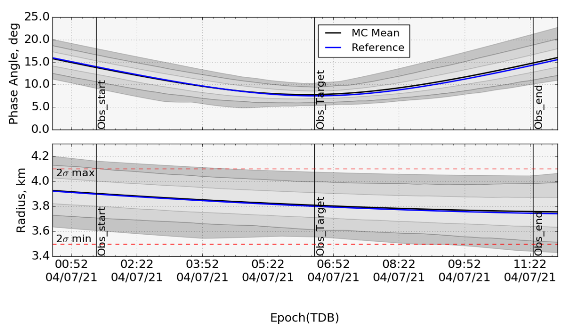
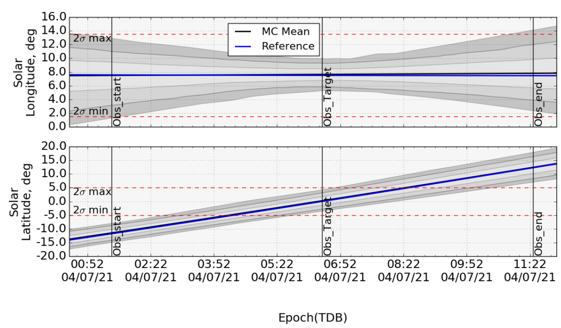


Figure 6: PTO phase reference trajectory Bennu-relative range and phase angle with 1, 2, and 3σ Monte Carlo errors



(a)



(b)

Figure 7: PTO science trajectory profile with 1, 2, and 3σ Monte Carlo errors. (a) Bennu range and phase angle and (b) solar longitude and latitude.

RETURN TO BENNU OPNAV CONOPS

Development of the OpNav ConOps for the return to Bennu flyby required substantial analysis and consideration, as many aspects of the return to Bennu were more challenging than any prior mission phase.

OD Covariance Analysis

Orbit determination (OD) covariance analysis was required to assess the need for image mosaics in the OpNav ConOps, as well as inform the OD delivery and ephemeris uplink schedules. The analysis was performed three times as the trajectory and maneuver plans evolved, each providing new insight to further develop the ConOps. Early results demonstrated the post-TAG trajectory knowledge errors required 2-by-2 mosaicking with MapCam to guarantee successful acquisition of Bennu, which hadn't been imaged since October 23rd, 2020.[8] The study also determined that 3-4 days of MapCam imaging would sufficiently reduce the Trajectory State Errors (TSEs) to guarantee Bennu would be in the narrow angle PolyCam field-of-view (FOV) without any required mosaics.[8] It was also determined that following acquisition, a relaxed weekly ephemeris update schedule would still guarantee Bennu remains in the MapCam FOV up until the PTO5 maneuver, with 3-σ confidence except for the final day before the next burn update. The team decided to accept this small risk of Bennu drifting outside of the MapCam FOV, and planned to do redundant imaging with NavCam[9] to serve as a backup.

The final iteration of the covariance analysis used a filter setup that estimated the spacecraft state, Bennu ephemeris, solar pressure, small forces based on scheduled desats, the 5 PTO finite burns with current best estimate (CBE) burn uncertainties, and Bennu GM. The initial state was pulled from the operational OD296 solution with an epoch of 03-JAN-2020, along with a correlated covariance with the Bennu ephemeris. Stochastic parameters included quadratic accelerations on the spacecraft body $O(1e-13km/sec^2)$ as well as per-pass range biases due to low sun-earth-probe (SEP) angle. Consider parameters included Troposphere and Ionosphere media errors, polar motion, UT1, and DSN Station Locations.

The covariance data simulation included Deep Space Network (DSN) range and Doppler, as well as some preliminary assumptions about the OpNav imaging schedule and performance. DSN data was simulated at two tracks per day, including a 5-hour high gain antenna (HGA) track on Goldstone and an 8-hour low gain antenna (LGA) track on Canberra. The DSN range and Doppler weightings were adjusted to account for potential issues at lower SEP angles.[10]

Simulated OpNav observables were scheduled daily starting February 23rd, with daily measurements through March 19th, and three measurements per day starting thereafter through the final DCO for the flyby on April 5th. PolyCam and MapCam centerfinding observables were assumed until the range allowed for correlation of MapCam landmarks starting on March 22nd, and NavCam landmarks starting April 1st. Prior to March 3rd, centerfinding measurements were deweighted to 1 px + 10% of body radius to account for potential issues at high phase angles and uncertain ranges; thereafter, the centerfinding measurements were weighted at 1px+1% body radius. The v42 Bennu shape[11,12] landmark vectors were used to simulate the MapCam and NavCam landmark observables, with weights of 4px and 2px, respectively, and the following filtered constraints on the observable landmarks:

- Ilumination angle < 90 deg

- 0 deg < Emission angle < 68 deg
- Image resolution up to 4x landmark resolution
- 66% of the viewed landmarks correlate

Figure 8 illustrates the navigation and uplink schedules derived from the development of the maneuver, orbit determination, and optical navigation concepts of operations, spanning from the re-acquisition OpNavs in Week 8 through the flyby and final OpNav imaging in Week 14. Each maneuver has a DCO three days before execution, with a 48-hour ground turnaround before the nominal uplink, and an additional backup uplink opportunity the day of each burn. In addition to the OD deliveries to support the maneuver late updates, two additional OD deliveries were required to reconstruct PTO3/PTO4 as well as maintain the on-board ephemeris after those burns.

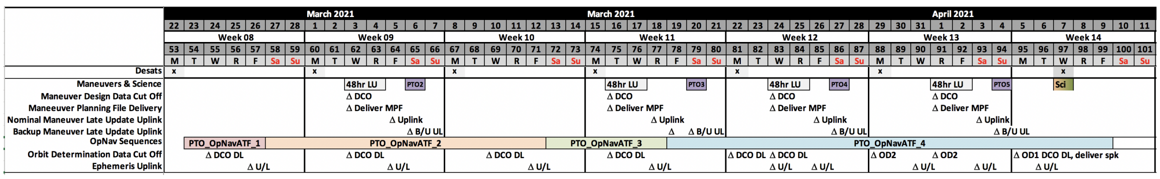


Figure 8: Navigation delivery and uplink schedule

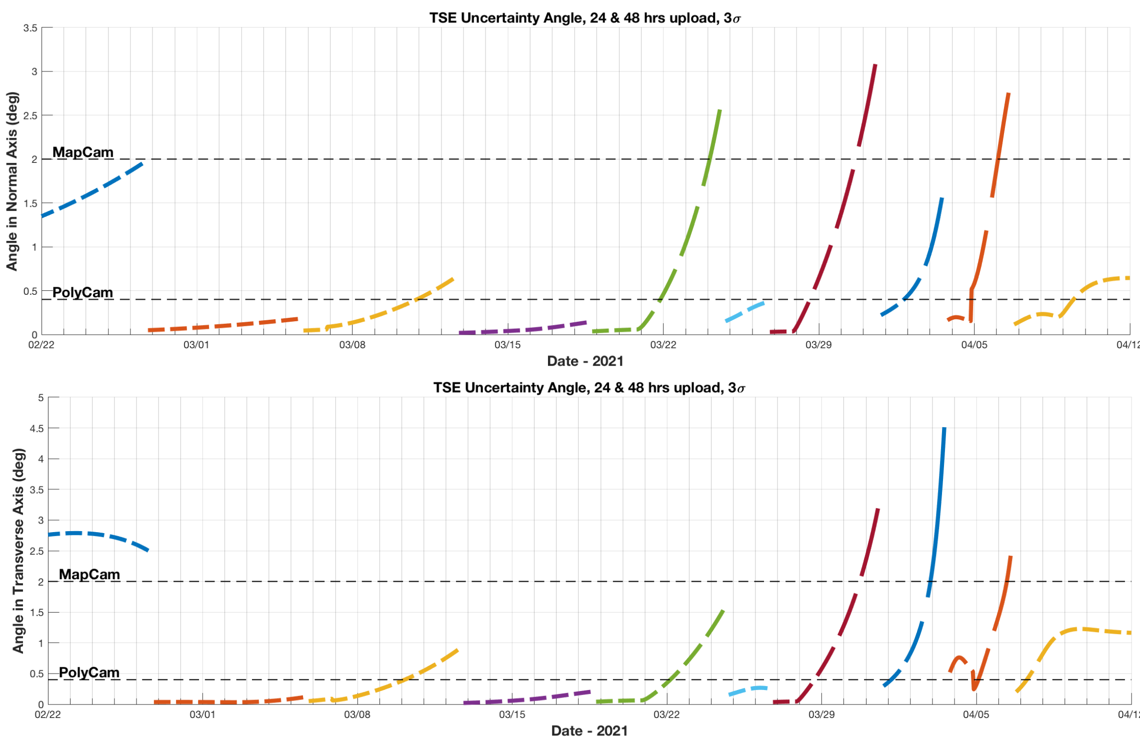


Figure 9: Predicted trajectory state errors (3-σ) along the normal and transverse axes. Each colored line represents a unique onboard ephemeris based on an OD solution, following the schedule in Figure 8. The half-angle FOVs for PolyCam and MapCam are shown to demonstrate when Bennu is at risk of falling outside the instrument FOV.

Exposure Analysis

Figure 6 illustrates the significant uncertainties in both range and phase angle based on the Monte Carlo analysis. This circumstance required the OpNav team to analyze exposure times for a variety of dispersed trajectories that were selected to bound the brightest and dimmest signals. The wide range of phase angles across the return trajectory precluded finding one exposure that would work for all images. However, we managed to find optimal exposure times for each instrument that were sufficient throughout the trajectory, with the exception of a 5-day period from March 13th to March 18th 2021 where the exposures had to be reduced due to the low phase angle. Additionally, the NavCam images taken as ride-along observations during the Science Observation Window (SOW) were reduced due to the brief period of low phase angle.

OpNav Imaging Plan

The OpNav imaging ConOps required four unique reusable sequences, in addition to the ride-along imaging during the SOW. Table 4 summarizes the dates, pointing specifications, imaging frequency, instruments used, and their exposure times. Each observation was taken as a pair of images with two exposure times: a short exposure optimized for imaging Bennu with sufficient SNR, and a long exposure optimized for detection of background stars.

Table 4: OpNav Imaging Sequences

Sequence Name	Date Span	Pointing Spec	Imaging Frequency	Instrument Exposures
PTO_OpNavATF_1	2/23-2/26	2x2 Mosaic	1x/day	MapCam 5ms, 4s
PTO_OpNavATF_2	2/27 – 3/12	Nadir	1x/day	MapCam 5ms, 4s PolyCam 5ms, 4s
PTO_OpNavATF_3	3/13 – 3/18	Nadir	1x/day	MapCam 3ms, 4s PolyCam 3ms, 4s
PTO_OpNavATF_4	3/19 – 4/9 except 4/7	Nadir	3x/day	MapCam 4ms, 4s NavCam 10.3ms, 5s
SOW	4/7	Ride-along	2 bookending SOW	NavCam 4.2ms, 5s

POST-TAG PERFORMANCE AND RESULTS

A summary of the final maneuver design parameters, reconstructed values, and estimated uncertainties are summarized in Table 5. Notably all maneuvers performed well below 1σ of their expected error, even the small TCM maneuver components of PTO1. The only exception to this is the Δv magnitude of PTO5, which showed a 1.23σ overburn.

Figure 14 shows the same nominal trajectory profile as Figure 6, but adds the reconstructed, as-flown, spacecraft trajectory in red. The phase angle in particular closely matches the reference in the period between PTO1 and PTO2, which allowed OpNav imaging to resume as planned on February 23. A closer view of this plot in the post-PTO3 time frame is provided in Figure 15, which shows the actual trajectory continued to follow the reference trajectory closely throughout the entire return to Bennu, largely within 1σ of the expected Monte Carlo errors.

Table 5: PTO Phase Maneuver Performance

Maneuver	Date (UTC)	Parameter	Nominal Value	Estimated Value	*A-priori* Sigma	Estimated Sigma	Correction	Correction / *A-priori*
PTO1a	14-Jan-2021	ΔV, cm/s	73.818	73.990	0.414	0.353	0.173	0.418
	19:44:21	RA, deg	154.896	154.514	0.785	0.475	-0.382	-0.487
		Dec, deg	-2.215	-1.887	0.785	0.353	0.327	0.417
PTO1b	14-Jan-2021	ΔV, cm/s	73.830	73.748	0.414	0.357	-0.082	-0.198
	20:15:39	RA, deg	83.115	83.462	1.884	0.800	0.348	0.185
		Dec, deg	65.379	65.517	0.785	0.491	0.138	0.176
PTO2	06-Mar-2021	ΔV, cm/s	34.169	34.2121	0.098	0.003	0.042	0.425
	20:00:00	RA, deg	307.018	307.266	0.332	0.005	0.249	0.750
		Dec, deg	-28.385	-28.589	0.292	0.008	-0.204	-0.701
PTO3	20-Mar-2021	ΔV, cm/s	39.147	39.168	0.112	0.002	0.021	0.185
	20:00:00	RA, deg	71.199	71.044	0.327	0.004	-0.156	-0.476
		Dec, deg	-26.946	-26.729	0.292	0.003	0.218	0.747
PTO4	27-Mar-2021	ΔV, cm/s	25.760	25.779	0.074	0.003	0.019	0.256
	20:00:00	RA, deg	221.222	221.354	0.311	0.006	0.132	0.424
		Dec, deg	-20.276	20.080	0.292	0.003	-0.196	-0.673
PTO5	04-Apr-2021	ΔV, cm/s	10.489	10.530	0.033	0.002	0.041	1.226
	20:00:00	RA, deg	130.796	130.652	0.299	0.008	-0.144	-0.481
		Dec, deg	-13.027	-12.848	0.292	0.005	0.179	0.613

The OpNav acquisition with 2-by-2 MapCam mosaics resulted in Bennu being captured in two of the four observations on February 23, in the region where the two fields overlapped. By the fourth and last day of mosaicking, Bennu had drifted to only one of the four MapCam footprints. Since the *a priori* trajectory was quite uncertain for processing the initial high-phase images, the team reprocessed the images after the first internal OD solution was generated, which refined the observables on the order of 0.6-0.7 pixels.

The first ephemeris update uplinked on February 26 resulted in Bennu being perfectly centered in the MapCam FOV for the start of nadir imaging on February 27. As predicted by the TSEs plotted in Figure 9, Bennu started clipping the edge of the PolyCam FOV on March 11, and was fully out of the FOV by March 13. Landmark-based OpNav[13,14] was initialized well before the covariance analysis conservatively assumed, due to reasonable correlations at high resolution ratios (image-to-maplet ground sample distance (GSD) around 9) starting on February 27 for PolyCam, March 13 for MapCam, and March 25 for NavCam. Both KinetX Image Processing (KXIMP)-based[14] centerfinding and stereophotoclinometry (SPC)-based landmark OpNav techniques[15,16] were used to process the images throughout the remainder of the final encounter. The degradation in the NavCam throughput (due to dust contamination during TAG[17]) was noticeable in the images due to increased stray light around Bennu. However, the increased signal did not appear to affect the NavCam observables, which compared well to the non-contaminated MapCam PAN filter. Only on April 9th, after the flyby, was the phase angle so great in NavCam to cause too much stray light signal to rely on stars for attitude.

The post-fit residuals for the KXIMP centerfinding method are plotted in Figure 10. The residuals are largely bounded within $\pm$ 1 pixel and 1-σ standard deviations fall between 0.18 and 0.36

pixels – well within the weighting assumed in the PTO covariance analysis. Figure 11 plots the residuals projected into the radial-transverse-normal (RTN) frame and converted to meters based on the GSD of each image. While centerfinding OpNav is not sensitive to radial errors, the post-fit transverse and normal residuals fall within $\pm$ 10 meters. A small bias is present in the early PolyCam images that were captured at extreme phase angle, which was anticipated and deweighted in both the covariance analysis and operational solutions. Figure 12 plots the post-fit residuals for the landmark observables, which are near zero-mean with standard deviations on the order of 0.2-0.4 pixels depending on the instrument. These residuals outperform the 2-4 pixel weights assumed in the OD covariance analysis. The residuals are converted to meters and projected into the RTN frame in Figure 13, which shows near zero-mean statistics with per-imager standard deviations between 0.2 and 0.7 meters. Overall the OpNav performance was exceptional during the challenging return to Bennu flyby.

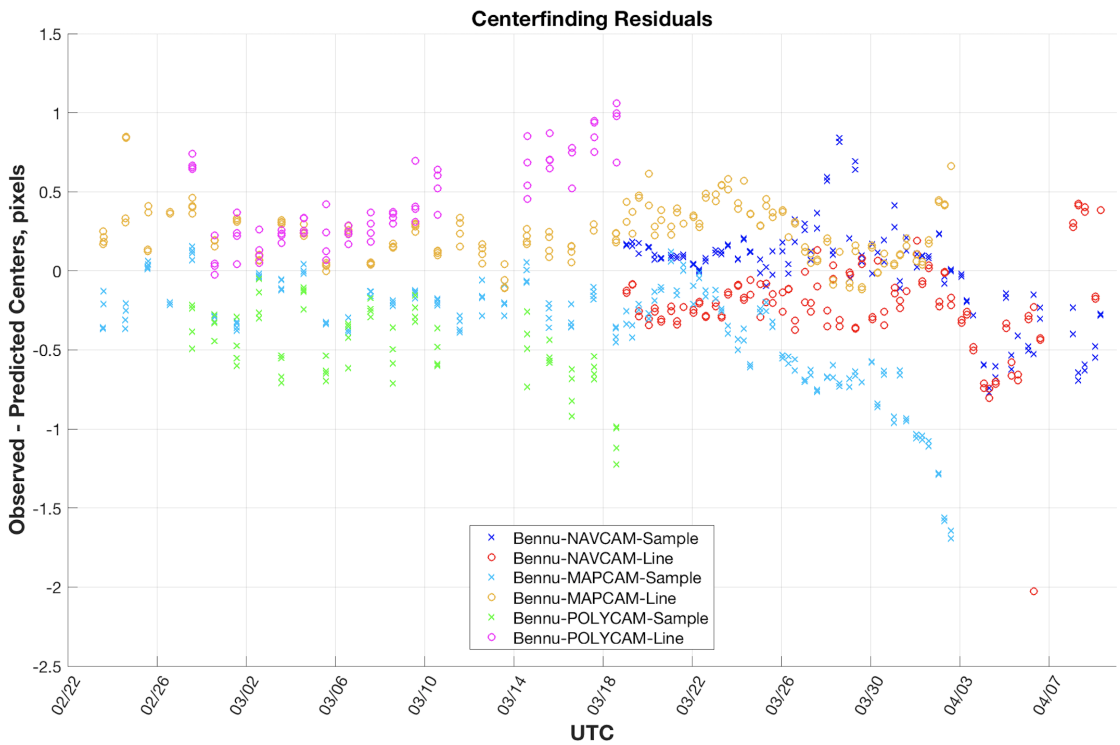


Figure 10: Post-Fit centerfinding residuals plotted in the instrument pixel/line coordinate frames.

Figure 16 is a repeat of Fig. 7 but with the reconstructed trajectory added in red. While the as-flown range and solar latitude are well below 1σ of the expected Monte Carlo errors, the phase angle is between 1 and 2σ high at the center of the observation window. This is not a concern as it is still well within the expected errors, and the higher phase angle implies that the spacecraft was further from the sub-solar point which is where there can be difficulty with pointing the spacecraft at nadir. This agrees with the solar longitude of the as-flown trajectory, which shows that the trajectory did not fly exactly South-to-North as designed. Instead the spacecraft started the observations closer to 0 degrees solar longitude and ended at nearly 12 degrees, passing through the 7.5 degree target approximately a quarter of the way through the observation period. This is due to an error in the location of the PTO5 maneuver prior to the start of the observation leg, which manifested from

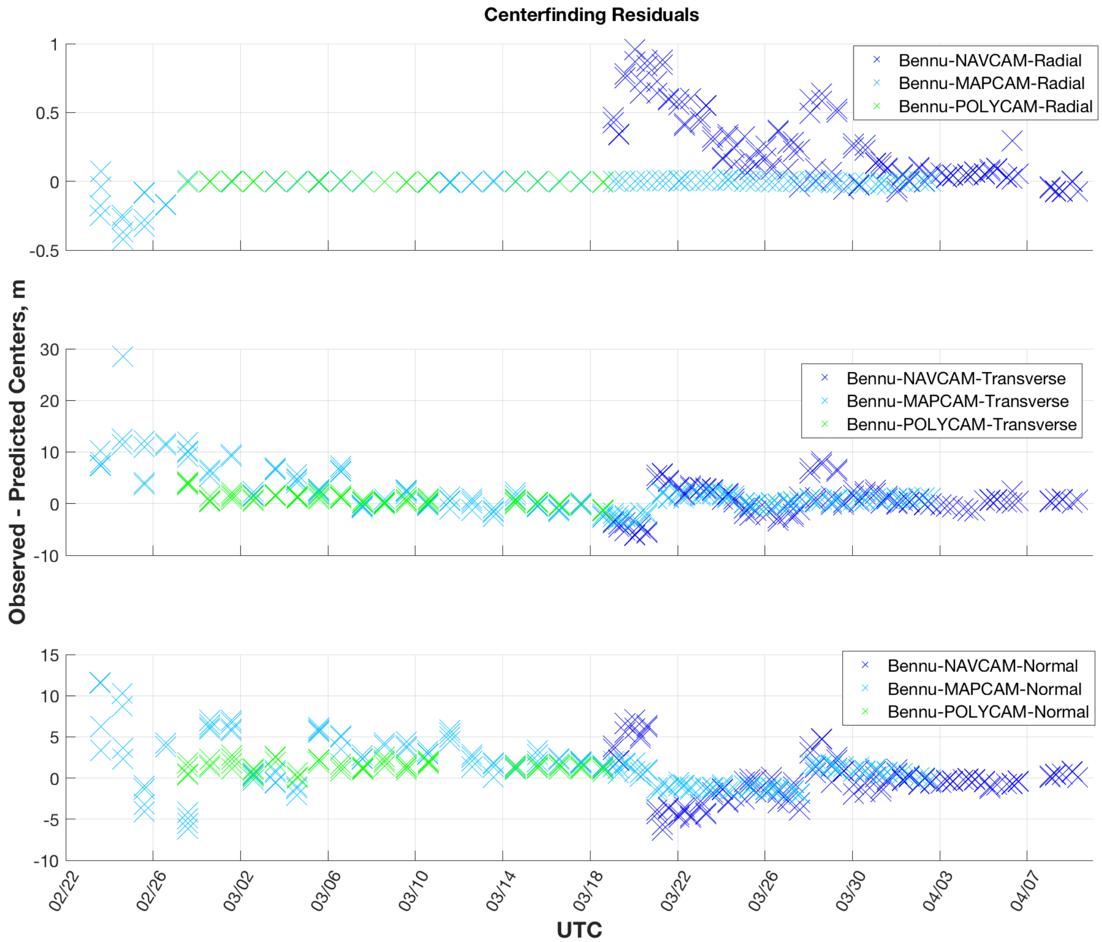


Figure 11: Post-fit centerfinding residuals projected into the RTN frame and converted to metric units.

error in the execution of the PTO4 burn. However, this error was still within expectations and did not detriment the science observations. While the observation start time was not adjusted for this phase as done during Detailed Survey, the calculated time shift in this scenario would have been -608 seconds, which is comparable with the flybys executed in previous phases.

Finally, Figure 17 shows a comparison of the pre-observation knowledge update and post-flyby reconstructed trajectories in the spacecraft radial, transverse, and cross-track directions. The shading represents the 1, 2, and 3σ predicted uncertainties generated from the covariance analysis performed months in advance, which were used as input for science observation planning. The predicted trajectory is seen to have been off by slightly less than 1σ in the radial and transverse directions during the observation period, while the normal direction showed very low predicted errors. The excellent performance in both delivery and knowledge errors led to a successful observation campaign, which provided the desired post-TAG imagery of the Nightingale sample site. Figure 1 shows a side-by-side comparison of the Nightingale site before and after sample collection, clearly showing the change in topography due to the spacecraft-surface interaction during TAG.

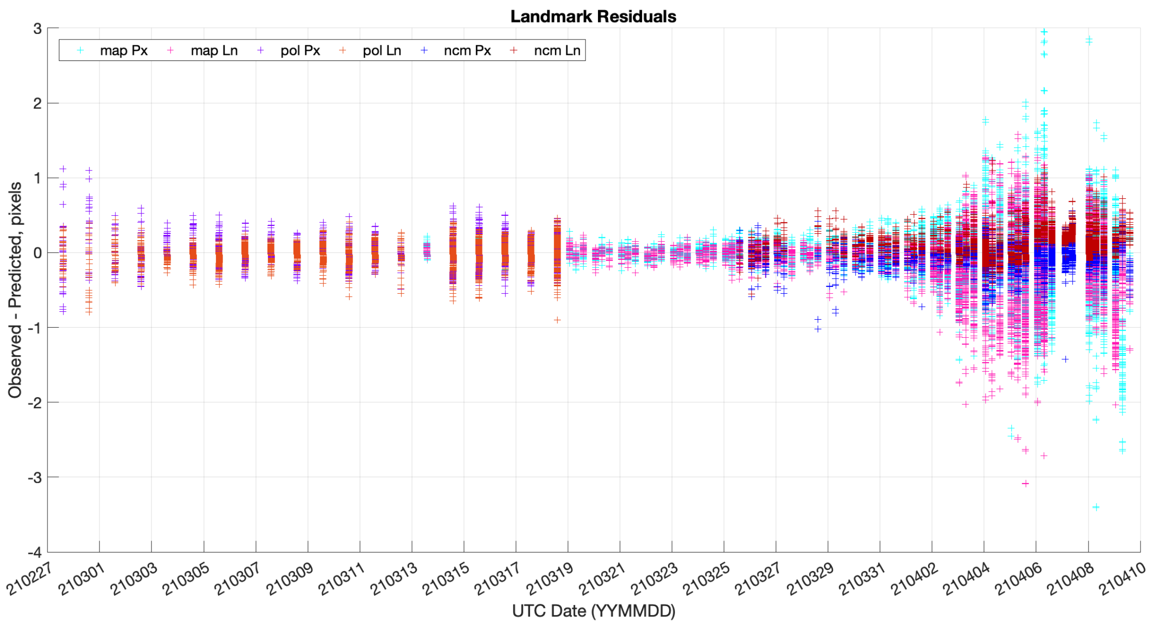


Figure 12: Post-fit landmark residuals plotted in the instrument pixel/line coordinate frames.

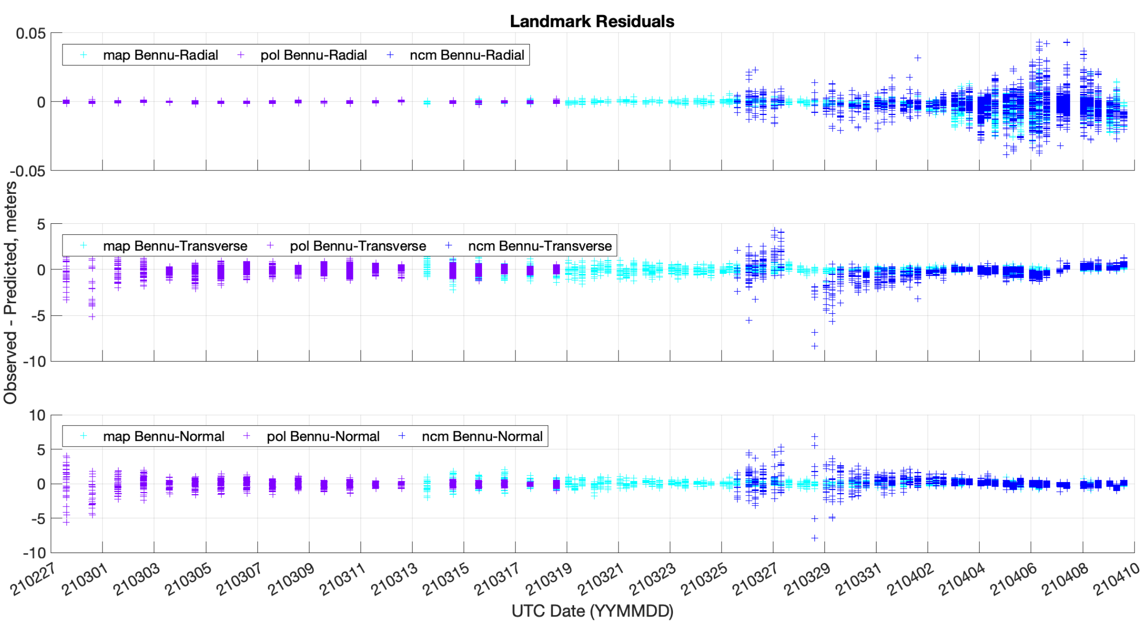


Figure 13: Post-fit landmark residuals projected into the RTN frame and converted to metric units.

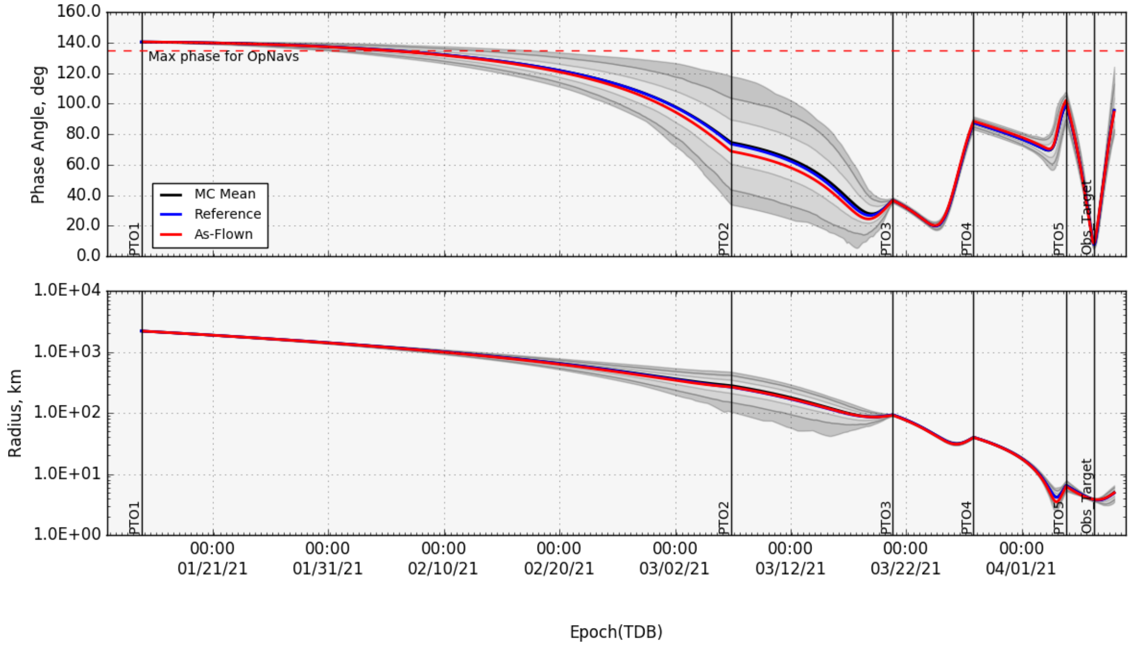


Figure 14: PTO trajectory profile showing Bennu range and phase angle with the as-flown trajectory in red.

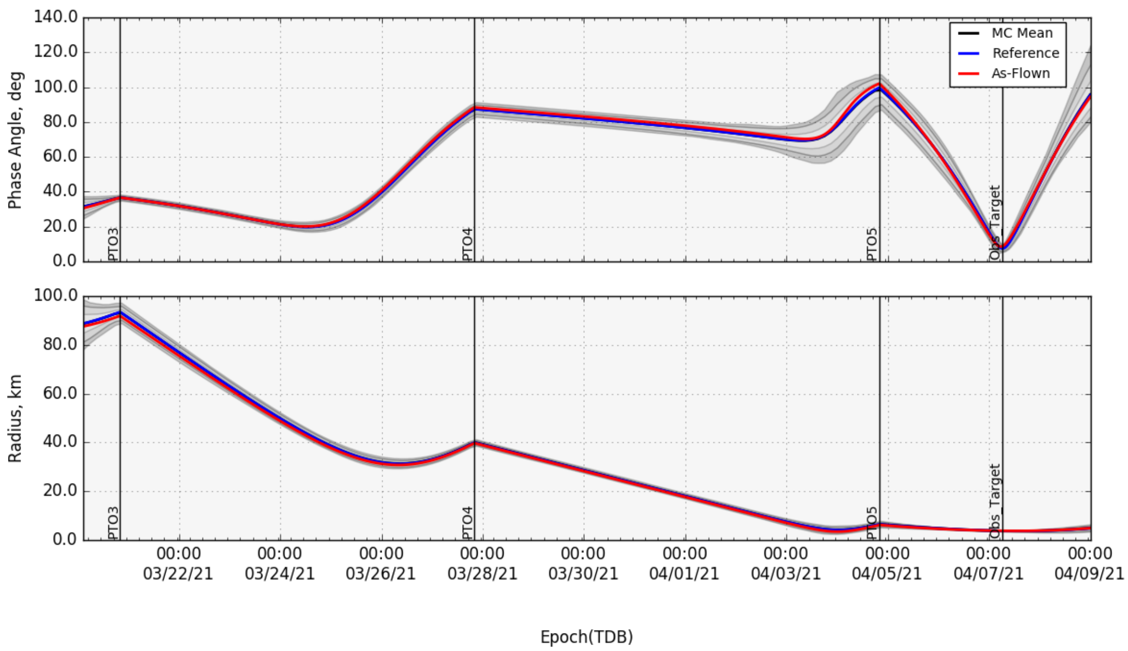
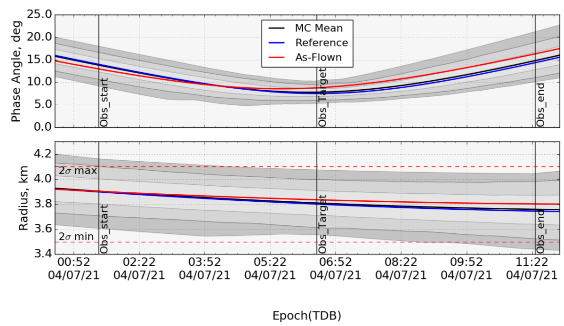
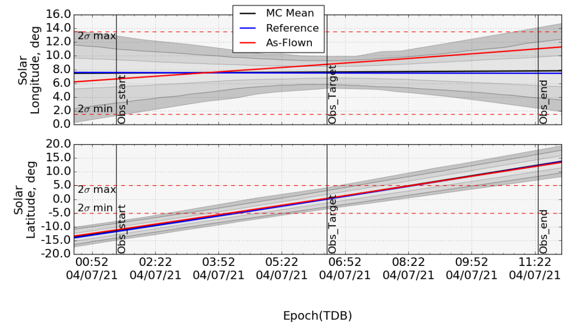


Figure 15: Zoom-in of the PTO trajectory profile starting just before PTO3 showing Bennu range and phase angle with the as-flown trajectory in red.



(a)



(b)

Figure 16: PTO science trajectory profile with the as-flown trajectory in red. (a) Bennu range and phase angle and (b) solar longitude and latitude.

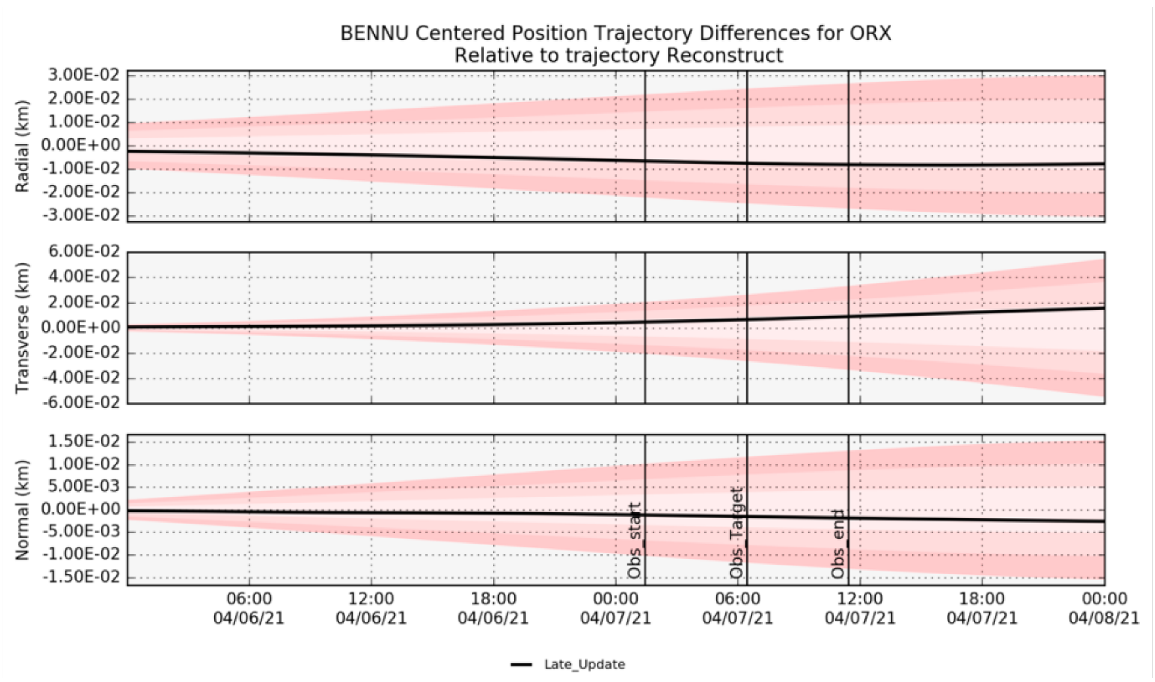


Figure 17: Comparison of the reconstructed and the pre-observation late update flyby trajectories

CONCLUSIONS

With a sample of asteroid regolith successfully in tow, the OSIRIS-REx mission was prepared to look ahead at returning the sample to Earth. Yet, the opportunity to image the surface one final time to investigate the spacecraft-to-surface interaction during TAG and obtain more insight on the internal composition of asteroid Bennu while still in close proximity was one that could not be missed. With the Earth return trajectory showing an optimal Bennu departure date in May 2021, OSIRIS-REx had the time and capability to perform an additional survey of the asteroid.

However, designing a trajectory and a Navigation ConOps after completion of TAG brought forth a slew of new constraints and requirements that did not have to be accounted for in previous mission phases. Above all else, the design required minimizing overall risk to the spacecraft and the stowed sample while still providing an effective observation opportunity of the asteroid surface. After several iterations, the Navigation team was able to create a design that satisfied the numerous spacecraft safety, scheduling, and observation constraints that were levied. The final design included just 5 maneuvers executed over the span of 3 months to bring the spacecraft from over 2000 km from Bennu to less than 5 km, and provided a safe trajectory that allowed the plan to be abandoned at any point were an anomaly to occur. OpNav imaging in particular required significant analysis in order to reliably reacquire Bennu, and required a more complicated ConOps than most other phases of the mission. By leveraging lessons learned from the previous 2 years at Bennu, the team was able to put together a plan that closed and could provide the desired imagery of the Nightingale TAG site. Successful execution of all aspects of this design and exceptional navigation performance led to the collection of the desired science observations during the final flyby in April 2021, which provided scientists the data necessary to obtain insight into the nature of the collected sample.

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